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Climate Change Vulnerability Assessments: A Review of Water Utility Practices

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Notice

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1. Executive Summary

Climate change poses a variety of challenges for water management, and there is a need to develop methods for understanding and managing risk. While much has been written about the projected impacts of climate change at the continental or regional scale, scientists are quick to caution decision makers about using projections based on global circulation models (GCMs) for local decision making. This 'uncertainty' about specific impacts on local systems has raised concern about the ability of water resource managers to plan for climatic and hydrological changes at the local scale, and has spurred recent activity to develop methods for understanding vulnerabilities, including how to downscale climate models.

This study examines and documents the steps taken by some of the leading utilities in an attempt to identify the emergent characteristics of water utility climate change vulnerability assessments. By examining the approaches taken and articulating the steps, information, and judgments needed for such decision making, we hope to contribute to the collaborative problem solving among the user and research communities who are working to further refine and validate such procedures.

The study describes the activities of eight water utilities who have conducted climate vulnerability assessments: East Bay Municipal Utility District, City of Boulder Utilities Division, Denver Water, Massachusetts Water Resources Authority, New York City Department of Environmental Protection, Portland Water Bureau, Lower Colorado River Authority, and Seattle Public Utilities.

The following general observations can be made. First, while the intention was to evaluate both drinking water and wastewater utilities in the systems evaluated, most vulnerability assessment work focused on water quantity and water demand and in only one case on water quality.

Second, while utility managers typically possess expertise about their systems, their hydrological and management models, and the local hydrology, they have more limited access to climate change information. Utilities are able to examine impacts on their operations due to changes in climate-sensitive variables (e.g., flow, demand), however, in many cases, in order to understand the changes in climate that affect those variables, utilities are engaging outside climate expertise.

Third, in each case study presented in this report, utilities are compensating for the 'uncertainty' about climate change by evaluating a range of scenarios or models, and in most cases the resulting information is used to test the robustness of existing decision making or planning against different future, plausible scenarios.

Climate change is a complex issue, and more work is needed to establish reliable practices for incorporating climate change into water utility decisions and planning. At the same time, utilities appear to have benefited from their various efforts to understand their potential vulnerabilities and to evaluate long term planning options. Despite the uncertainty, there are reasonable and prudent steps utilities and other water managers can take to better understand and manage climate risk.

2. Introduction

For many decades, water utilities have proactively assessed the ability of their systems to provide a reliable supply of drinking water or adequate wastewater services under assumptions of population change, municipal expansion (e.g., annexation), technological innovation, and changes in regulations. These were the foreseeable challenges utilities addressed to ensure that ratepayers received high quality water services at minimal cost.

Historically, utilities assumed stationarity of climate in their water resource planning – the idea that natural systems fluctuate within an unchanging envelope of variability. Recently, however, this assumption has been challenged, forcing managers to rethink future water resources planning and management with regard to climate change (Milly et al., 2008). In response, over the last decade, water utilities have expanded their risk assessment efforts to address changing climate conditions.

Generally speaking, vulnerability assessments done by water utilities are grounded in a thorough understanding of their water system. On a practical level, this means that vulnerability studies use a variety of tools and models that have been developed and refined to reflect the local hydrology, climate, infrastructure, operations, and demands that are unique to a particular water utility. Consequently, no single tool currently exists that can comprehensively address the vulnerability of diverse water systems to climate change. For example, most utilities have operational or management models that estimate the day-to-day operation of their water or wastewater systems. By necessity, these operational models are either unique to a particular utility (e.g., a proprietary system model) or in some cases, customized versions of a tool used by many utilities (e.g., the Water Evaluation and Planning, or WEAP, system model).

The purpose of this report is to illustrate the approaches used by water utilities to assess their vulnerability to climate change. This is a review of best practices in this emerging effort across the industry for the purpose of informing utilities considering engaging in this issue about the various methods used by their peers. The report does not judge or evaluate the efforts of utilities or the merits of different vulnerability assessment methods, but describes the efforts of eight utilities as broad approaches, tools, and methods worthy of consideration by other utilities depending upon their needs, available resources, and other factors.

In this report we examined the ways in which several water utilities evaluated their potential vulnerability to climate change. Utilities included in this study were identified from published studies on water resources and climate change, including six Water Research Foundation reports (Strange et al., 2009; WRF, 2010a, 2010b, 2010c, 2010d, 2010f), two reports by the Water Utility Climate Alliance (Barsugli, et al., 2009; Means et al., 2010), and participants in the ongoing Joint Front Range Climate Change Vulnerability Study (WRF, 2010e). We also included utilities selected from the list of participants in two recent workshops focused on water resources and climate change: the National Drinking Water Advisory Council's Climate Ready Water Utilities Working Group and U.S. Environmental Protection Agency's (EPA's) First National Expert and Stakeholder Workshop on Water Infrastructure Sustainability and

Adaptation to Climate Change (U.S. EPA, 2009).[1] In total, we identified 50 water utilities as potential candidates for in-depth case studies. Initial review, however, revealed that many of the selected utilities were interested in tracking the climate change issue and learning what others had done, but had not yet engaged in their own climate change vulnerability assessments. If this was the case, the utility was eliminated from the initial list for further study.

We identified five utilities that had published reports on their own climate change vulnerability work, and another five utilities that appeared to have conducted vulnerability work but had not published the modeling results. Because of time and resource limitations, the study was limited to eight of these 10 utilities. The two utilities not included were Inland Empire Utilities Agency and King County Wastewater Treatment Division. The eight utilities included in the assessment included:

- East Bay Municipal Utility District (EBMUD)
  - A water supply and wastewater utility serving 1.3 million customers.
- City of Boulder Utilities Division
  - A water supply and wastewater utility serving 113,000 customers.
- Denver Water
  - A water supply utility serving 1.3 million customers.
- Massachusetts Water Resources Authority (MWRA)
  - A water supply and wastewater utility serving 2.2 million customers.
- New York City Department of Environmental Protection (NYCDEP)
  - A water supply and wastewater utility serving 9.2 million customers.
- Portland Water Bureau (PWB)
  - A water supply utility serving 860,000 customers.
- Lower Colorado River Authority (LCRA)
  - A conservation and reclamation district that manages water supply along a 600-mile stretch of the Colorado River in Texas, operates six dams, and helps communities plan and coordinate their water and wastewater needs.
- Seattle Public Utilities (SPU)
  - A water supply utility serving 1.35 million customers.

Finally, we studied these eight utilities' climate change vulnerability analyses in depth to identify tools and approaches used by those water utilities in their assessments. The remainder of this report synthesizes the insights from the analysis of these eight utilities in the following sections: approaches to assessing climate change vulnerability, sources of climate information, modeling changes in water resources, summary, and recommendations for further study.

1. A forthcoming report from the Water Research Foundation (WRF, 2010d) offers case study information relevant to this report, but the final draft was not publicly available for inclusion in this report.

3. Approaches to Assessing Climate Change Vulnerability

Most water managers engaged in climate vulnerability analyses have a strong technical understanding of their water systems, including local hydrology, historical operating conditions, and standard operational practices.[2] However, they typically are not climatologists and have limited experience assessing risks from climate change. As a result, a water utility can either engage outside expertise to do a sophisticated exploration of the implications of climate change or they can make do with the information and capabilities readily available. Utilities that choose not to engage outside experts are generally limited to analyses based on their internal understanding of their water system and/or sensitivity analyses to assess what hypothetical climate changes would mean for their water system. In contrast, utilities that engage outside expertise can generate climate projections specific to their watershed. This more resource-intensive approach enables computationally sophisticated vulnerability analyses.

Approaches to assessing climate change risks are generally classified as either "top-down" modeling assessments or "bottom-up" threshold analyses (e.g., Miller and Yates, 2006; Freas et al., 2008; Stratus Consulting and MWH Global, 2009). This categorization is useful, and, generally speaking, utilities choose one of these two approaches to initiate their climate vulnerability assessment. However, it should be noted that these two approaches are not mutually exclusive and utilities often incorporate elements of both, either in series or in parallel. The choice of one approach over another, however, has significant implications for study design and resource needs, making them useful as categorical descriptions. The following utilities initially used a top-down assessment:

- City of Boulder Utilities Division
- Denver Water
- MWRA
- NYCDEP
- PWB
- SPU

The following utilities initially used a bottom-up assessment:

- EBMUD
- LCRA

In general, top-down assessments are model and data driven. They often are more time and resource intensive than bottom-up assessments, sometimes requiring expertise beyond the

2. Furthermore, most utilities take land use changes, population projections, and economic development into account in infrastructure design and operational planning. Climate, however, often gets lumped in with hydrological considerations and does not rise to the level of an independent planning consideration.

capacity of many utilities. In general, bottom-up assessments are driven by knowledge of the utility system itself. Such assessments often focus on defining critical system thresholds or specific decisions that may be sensitive to climate change. This can often be done qualitatively, and the necessary expertise often resides within the utility. As suggested above, these two approaches are not mutually exclusive.

3.1 Top-down Modeling Assessments

Six utilities in our study initiated their vulnerability assessments with a top-down approach: Boulder Utilities (Smith et al., 2009), Denver Water (Laurna Kaatz, personal communication, April 8, 2009), MWRA (Stephen Estes-Smargiassi, personal communication, February 26, 2010), NYCDEP (2008; Major et al., 2007), PWB (Palmer and Hahn, 2002), and SPU (Palmer, 2007). This method projects future climate conditions specific to the watershed of concern and is the most computationally and resource intensive of the analysis approaches used by utilities. Because of this, the top-down modeling assessments done by the utilities examined for this report were often completed by the water utility in conjunction with an academic institution or consulting firm with expertise in climate modeling. For example, SPU and PWB partnered with the University of Washington's Climate Impacts Group (UW-CIG), NYCDEP partnered with the City University of New York Institute for Sustainable Cities (CISC) and Columbia University's Center for Climate Systems Research (CCSR), LCRA used CH2M Hill as a consultant, and the City of Boulder Utilities Division engaged Stratus Consulting and Hydrosphere (now AMEC).

Top-down assessments can involve relying on historic hydrology, using paleoclimate records, engaging in literature reviews, or they can be done using climate projections. All these options are discussed in more detail in Section 3 (Sources of Climate Information). By far, the most common form of top-down assessment involves generating downscaled climate projections for a utility's local watershed using global climate model (GCM) output. To do this, the analysis generally includes assumptions about future emission levels (i.e., global socioeconomic development scenarios), the effects of those emission levels on global climate (e.g., temperature and precipitation), the translation of global climate effects to the region or watershed, and the specification of climate changes on hydrology (e.g., streamflow), as well as operational, management, and demand models.

All of the utilities we studied in depth assessed a number of climate variables; however, the most common climate variables of interest were those that fed into their watershed-specific hydrology models or system-specific management or operations models. Most often, this included temperature and precipitation data or streamflow data at the spatial and temporal scales of each individual utility's hydrology, management, operations, or other models.[3] Therefore, to make meaningful comparisons in this study, we focused our investigation of the different modeling approaches to develop projections of temperature and precipitation. It is worth noting, however,

3. This conclusion was also reached in a study of the Water Utility Climate Alliance utilities (Barsugli et al., 2009).

that some utilities also investigated issues of special concern for their water system. For example, NYCDEP was concerned about source water quality, especially due to heavy precipitation events and resulting turbidity, and MWRA was concerned about likely impacts on the safe yield of its sources.

Top-down modeling has three important subcategories: scenario analyses, sensitivity analyses, and paleoclimate data or historic climate observations to define temperature and precipitation patterns for water system planning purposes. Each of these subcategories is described in detail in the following sections.

3.1.1 Scenario analyses

The scenario approach to a top-down assessment begins by defining at least one, but more commonly two or three plausible greenhouse gas (GHG) emission futures that merit consideration by a water utility. A scenario analysis then works step by step through GCMs, downscaling those results,[4] and finally using those results in water system specific hydrology, demand, operational, and/or management models as appropriate to investigate the vulnerability of a water system to each scenario. Section 3.4 (Climate Projections) discusses these individual steps in greater detail. In many cases, scenarios are developed to capture a wide range of plausible futures by incorporating an extensive range of models, emissions scenarios, and projected demands. As an example, the SPU study applied the scenario analysis technique and used GCMs and socioeconomic projections to assess a “middle of the road,” a “warmer and wetter,” and a “warmer and drier” scenario. MWRA’s approach used the outcome of all GCMs to estimate the probability distributions of likely changes in temperature and precipitation and then utilized those distributions in the statistical downscaling. This methodology, developed at NCAR, avoids using a scenario tied to a single GCM.

3.1.2 Sensitivity analyses

Another form of the top-down approach uses a sensitivity analysis, incorporating the use of incremental changes in climate such as 1º, 2º, and 3ºC (1.8º, 3.6º, and 5.4ºF) annual temperature increases combined with +/- 0%, 10%, or 20% annual changes in precipitation.[5] PWB used this type of sensitivity analysis to bracket a plausible range of climate-altered future hydrology. But utilities can also engage in a sensitivity analysis, as was done by EBMUD, with a bottom-up

4. The term “downscaling” has come to mean the use of higher resolution regional climate models (RCMs; dynamic downscaling) or complex statistical approaches (statistical downscaling), but in this case can also refer to simple downscaling, which typically involves adding the temperature increase in a GCM grid to observed temperatures for stations in the grid box and multiplying the percentage change in precipitation by the observed precipitation record.

5. Sometimes sensitivity analyses use arbitrary increments, but they can also be informed by the scientific literature. Sensitivity analyses can use different changes in temperature and precipitation by season, but this approach was not used in the vulnerability analyses investigated for this report.

approach to avoid the computationally and resource intensive steps of a scenario analysis. A sensitivity analysis does not require using GHG emissions projections, using climate model projections, or downscaling climate model output.

3.1.3 Paleoclimate or historic analyses

A third top-down approach incorporates paleoclimate studies or historic climate observations to define temperature and precipitation patterns for water system planning purposes. The method often defines a worst case scenario (e.g., three consecutive years of the drought of record) or examines the water system effects of droughts in the paleorecord outside of observed variability. While the City of Boulder Utilities Division, Denver Water, and EBMUD used paleoclimate studies to complement their climate change vulnerability studies, none of them relied exclusively on paleoclimate or conservative extrapolations from historic data.[6]

3.2 Bottom-up Threshold Analyses

The bottom-up approach to climate change vulnerability assessments is grounded in knowledge of the water system itself. Using this approach, a qualitative system assessment is done to determine which system components are potentially vulnerable to change. The results of the assessment can be used to focus further study on specific impacts of concern.

EBMUD, which used this approach, stated, "In a 'Bottom-Up' approach, the most critical vulnerabilities of the District's water supply system are identified, the causes of those vulnerabilities are articulated, and then steps are taken to better address and solve the vulnerability in the face of climatic uncertainty" (EBMUD, 2009, p. 4-16). They noted their concept of a bottom-up approach is adapted from the AwwaRF (now the Water Research Foundation) publication, *Climate Change and Water Resources: A Primer for Municipal Water Providers* (Miller and Yates, 2006).

More specifically, the EBMUD research approach involved a portfolio evaluation that first identified potential portfolio components (e.g., new reservoirs, expanded reservoir storage, increased conservation, conjunctive use, water reclamation, desalination, interbasin transfers), screened those components for technical, environmental, and economic feasibility, and then constructed alternate portfolios of multiple components that could meet projected demands (e.g., increased conservation and conjunctive use, or water reclamation and interbasin transfers). Then, a preliminary portfolio analysis was conducted using a combination of the WEAP system model and the district's EBMUDsim model – known collectively as the "W-E model." Portfolios that performed poorly under current hydrological conditions were eliminated and the remaining portfolios were subjected to detailed analyses under anticipated climate change conditions using

6. The lack of evidence for sole reliance on these types of analyses in the cases investigated for this report is largely a product of the case selection methodology, which focused on utilities with a published record of sophisticated vulnerability work.

the W-E model. By screening out portfolios that perform poorly under current conditions, EBMUD implicitly limited options to those that could be implemented under current conditions without significant reduction of reliability, but which presumably would improve the system under climate change relative to the current system. By comparing the climate change scenarios to a baseline scenario, the sensitivity of the EBMUD water system to each component was assessed to identify critical vulnerabilities and identify portfolios that addressed those vulnerabilities.

LCRA also used a bottom-up approach, and in CH2M Hill's report for the authority, the threshold approach was defined in this way: "This threshold approach identifies system components that are dependent on the status of climate variables (e.g., precipitation, temperature, etc.) and the overall system risk to climate change, resulting in a preliminary risk assessment based on the professional judgment of experts who know the system and the planning area" (CH2M Hill, 2008, p. 3-2). This approach is a qualitative or semi-quantitative analysis that consisted of (1) identifying the climate variables of importance and exploring the sensitivity of LCRA to these variables; (2) determining water system responses to a range of potential climate changes; (3) assessing the vulnerability of LCRA to climate change impacts; (4) assessing system performance according to the uncertainty associated with climate change factors driving LCRA vulnerability; and (5) evaluating overall system risk and identifying areas in need of further analysis.

3.3 Policy Environment as a Constraint

A key constraining factor affecting any utility's ability to assess climate change vulnerability is the level of support of the local community about climate change, in particular utility ratepayers, boards of directors, and locally elected officials. In many circumstances, it is not feasible for a utility to engage in a "climate change" vulnerability study because there is no political support for the effort. Therefore, the policy environment directly impacts a utility's approach to climate change vulnerability assessment. For example, New York City Mayor Michael Bloomberg has taken climate change seriously during his tenure, providing political support for climate change adaptation efforts. As a result, NYCDEP has been able to do sophisticated analyses and make long-term investments to assess potential risks. Many water resource managers in less supportive political environments, however, do not have the political support needed to take on climate change directly or explicitly and must use historic or paleoclimate data rather than downscaled climate model data to justify operational changes or investments that require a rate increase. If support does not exist for climate studies, a water manager might elect to do a sensitivity analysis as a lower-profile way to understand the potential vulnerabilities of their water system to changes in climate conditions – climate change or climate variability.[7]

7. Water utilities might also select these methods for other reasons, such as a lack of funding or because uncertainty in the projections does not yield enough value added to justify the effort of an intensive climate change vulnerability assessment.

Vulnerability to changing environmental conditions is often incorporated into contemporary utility planning efforts even if those efforts are not billed as climate change vulnerability assessments. Indeed, during research for this report, we discovered a utility that reported taking sea level rise into account in their infrastructure design as far back as 1989, but without advertising the analysis as "climate change." In summary, the policy environment in which a utility operates may dictate what approaches to climate vulnerability assessment are acceptable, how such studies are conducted, what data sources are used, and other important aspects of vulnerability assessment design.

4. Sources of Climate Information

Regardless of how a climate change vulnerability assessment is framed, climate information that operates at the spatial and temporal scale of a utility's hydrology, planning, and/or operational models is almost always used in vulnerability assessments.[8] Most commonly, temperature and precipitation estimates at daily, weekly, or monthly timesteps are input into utility-specific hydrology, demand, operations, and/or management models to assess the effects of different climate conditions on water supply or wastewater services.[9]

Temperature and precipitation estimates can be derived from a number of sources, including the instrumental record, paleoclimate studies of variability beyond the historical record, literature reviews, and downscaling GCM projections to utility-specific watershed(s) to generate projected future climate conditions. These sources of climate information have different associated logistical and resource constraints and each is explored in more depth below. The key criterion for selecting a source of climate information is that the approach and the data can be justified, sometimes only to a technical audience, but increasingly to ratepayers, boards of directors, and elected officials as well.

Utilities need credible climate information in order to consider climate change impacts on their water systems. Historically, most utilities that address climate change issues have relied on partnerships with academic and research institutions to help them select appropriate climate data, however, many utilities are increasingly turning to private consulting companies to help them with this task. Small- and medium-sized utilities, however, often lack the financial resources needed to engage consultants to provide technical guidance on climate change vulnerability studies and their ability to partner with academic institutions is not clear. The scalability of the climate information approaches described below must be carefully considered for potential

8. Note that climate information includes more than GCM output, including historic weather station data, stream gauge data, paleoclimate reconstructions, and more. However, when GCM output is used, it typically has to be downscaled or assumptions made to reduce the temporal and spatial resolution to be usable in utility hydrology or operational models.

9. Climate models often provide monthly average changes that must then be combined with the observed record at a daily timestep to generate projected daily changes in climate.

applicability beyond the relatively large and highly-resourced water utilities that have led the movement to consider climate change explicitly in their infrastructure and operational planning.

4.1 The Instrumental Record

The instrumental record is often used to define utility-specific models for demand, hydrology, operations, and management. These models can be simple statistical relationships or complex physical models of local hydrology that incorporate vegetation cover, aspect, slope angle, and soil type in addition to precipitation and temperature. Regardless, the instrumental record forms a fundamental basis for most utility vulnerability assessments in one form or another.

Utility vulnerability assessments have historically used the drought of record or flood of record to assess the vulnerability of a water system by applying the most extreme climate conditions on record to contemporary circumstances. In many cases, this type of analysis can be useful for identifying current vulnerabilities of a water system to current climate.[10] Although none of the utilities discussed in this report relied exclusively on this assessment methodology, many utilities still routinely rely on this method due to its familiarity and ease of use.[11] It is important to note that using only the instrumental record implicitly retains the assumption of climate stationarity – fluctuation within an unchanging envelope of variability – as observed typically within the last century or less.[12]

4.2 Paleoclimate Data

Some researchers have begun developing proxy records for precipitation and streamflow based on tree rings and geological evidence.[13] These researchers have found evidence of dry periods prior to the 20th century that were more persistent and perhaps more intense than what is observed in the instrumental record (e.g., Woodhouse and Lukas, 2006a). Because natural climate variability can often be quite large compared to changes projected from climate change, some utilities have used paleoclimate data as a complement to their climate vulnerability assessments.

10. With a changing climate, there should be more caution about interpreting the historic record. What may have been a 100-year drought or flood calculated from the historic record may shift significantly with projected climate change, or even by adding the paleorecord to historic data.

11. For example, both Contra Costa Water District and Santa Clara Valley Water District in California make conservative assumptions about "worst-case scenarios" for drought planning instead of engaging in climate change-specific studies as described in this report.

12. The exception to this would be to identify trends in the historic record and extrapolate them into the future. None of the utilities surveyed carried out such an approach.

13. The scientific field of dendrohydrology involves using tree-ring qualities, such as the width of the annual growth rings, to estimate pre-instrumental streamflow of a specific river.

For example, EBMUD used paleoclimate reconstructions of riverflow on the Sacramento River to examine the resilience of their drought planning sequence (Meko and Woodhouse, 2005). Their use of paleoclimate data was largely qualitative, but the analysis demonstrated EBMUD's drought planning sequence would likely function adequately under the drought conditions evidenced in the paleorecord. Denver Water has also used 375-year tree ring reconstructions of the Colorado and Platte River basins in conjunction with their water supply simulation model – PACSM – to estimate the frequency and severity of drought within Denver Water's collection system (Woodhouse and Lukas, 2006a). Boulder Utilities used a 300-year tree ring reconstruction of hydrology for similar purposes (Hydrosphere, 2003).

Tree-ring reconstructions hold much promise because of an excellent network of tree-ring data, especially (but not limited to) the western United States (TreeFlow, 2010). The use of paleoclimate reconstructions, however, is limited because tree-ring reconstructions are not available for all areas, they can be difficult to translate into the modeling environment for water management, good relationships with hydrology have only been established for the growing season – giving an incomplete record of annual hydrology, and the instrumental records necessary for high-quality calibration of tree-ring data can be difficult to obtain. For these reasons, and because of the specialized skill set necessary to conduct such studies, paleoclimate data may not be feasible for many water utilities (Garrick and Jacobs, 2005).

4.3 Literature Reviews

Literature reviews can generate information for projected future climate conditions for many utilities at low cost. The most common sources for initiating climate literature reviews are the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC, 2007) and the U.S. Global Change Research Program's report *Global Climate Change Impacts in the United States* (Karl et al., 2009). The National Oceanic and Atmospheric Administration (NOAA) is currently developing a climate information web portal (http://www.climate.gov), and NOAA's Regional Integrated Sciences and Assessments (RISA) program offices often provide regional literature and data resources (http://www.climate.noaa.gov/cpo_pa/risa/).

With the dramatic increase of climate research across the United States, regional specification of GCM output can often be found in the scientific peer-reviewed literature or on web portals.

For example, EBMUD decided not to expend resources on developing its own downscaled climate projections because sufficient data could be obtained in works of the IPCC (2007), the U.S. National Research Council (NRC, 2002), and the U.S. Geological Survey (Dettinger, 2005). Using these data, EBMUD ran a sensitivity analysis on their water system using the following factors:

- Increased customer demand resulting from a 4ºC (7.2ºF) increase in air temperature between 1980 and 2040;
- Changes in the timing of runoff in the Mokelumne River corresponding to 2º, 3º, and 4ºC (3.6º, 5.4º, and 7.2º F) increases in air temperature; and

- Reductions in Mokelumne River runoff corresponding to a 10% and 20% decrease in precipitation.

EBMUD combined these three factors to derive seven scenarios that represented an adequate range of conditions to analyze the potential sensitivity of the EBMUD water system to climate change.

4.4 Climate Projections

The development of watershed-specific projected future climate conditions is the most computationally and resource intensive approach to gathering climate information. Data obtained by this method were employed by many utilities, including the City of Boulder Utilities Division (Smith et al, 2009), Denver Water (Laurna Kaatz, personal communication, April 8, 2009), SPU (Palmer, 2007), MWRA (Stephen Estes-Smargiassi, personal communication, February 26, 2010), NYCDEP (2008), PWB (Palmer and Hahn, 2002), and LCRA (CH2M Hill, 2008). Climate projections consist of three main elements: the use of socioeconomic scenarios of GHG emissions, the selection of GCMs, and the region-specific downscaling of climate model output. Each of these elements is described in greater detail below. Also described below is the innovative combination of climate projections with other data sources for analytical purposes.

It is important to note that the complexity and resource intensity of making climate projections for water resources is being rapidly reduced. For example, the U.S. Bureau of Reclamation now provides a downscaled dataset of statistically downscaled monthly climate projections from 1950 to 2099 that consists of 112 climate projections based on 16 climate models and three GHG emissions scenarios downscaled to a spatial resolution of 1/8 degree across the coterminous United States (Maurer et al, 2007). The National Center for Atmospheric Research (NCAR) is also developing a dataset of GCMs combined with different regional climate models (RCMs) (UCAR, 2007). As these datasets and tools become more widespread, the time and resource threshold to engage in climate projections likely will be lowered. CH2M Hill's assessment of the LCRA system used the Bureau of Reclamation dataset as the foundation for its analysis.

4.4.1 Climate scenarios

Utility climate scenarios generally consist of two distinct elements: GHG emissions scenarios and defined time periods. Probabilities have not been assigned to the emissions scenarios (they are all assumed equally likely to occur) and, as a result, probabilities have not been assigned to climate change scenarios.[14]

GHG emissions scenarios have been developed to identify plausible future global energy use, economic growth, land-use change, population growth, technological innovation, and other

14. NCAR has developed probabilities of regional changes in temperature and precipitation based on analysis of GCM output (Tebaldi et al., 2005, 2006), but these probabilities were not used by the utilities examined in this study.

factors that could affect future emissions of GHGs. Most utilities in our analysis used GHG emissions scenarios defined in the 2000 IPCC Special Report on Emissions Scenarios (SRES; see Box 1).[15]

In general, water utilities have selected two or three GHG emissions scenarios to provide substantially different future GHG emission levels. Using multiple GHG emissions scenarios avoids putting too much emphasis on any single projection of the future. For example, the SPU study used emissions scenarios A2 and B1; NYCDEP used emissions scenarios A2, A1B, and B1; and LCRA used emissions scenarios A2 and B1. While, by definition, these scenarios are equally plausible, water utilities have generally selected both a low emissions/environmentally friendly scenario (i.e., B1) and a high emissions/development-oriented scenario (i.e., A2) to ensure representation of a wide range of plausible futures.

Box 1. IPCC SRES scenarios.

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).
- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Source: Nakićenovic et al., 2000 (p. 4-5).

15. IPCC is now moving toward a set of scenarios based on radiative forcing and not tied to specific socioeconomic scenarios (Moss et al., 2010).

Furthermore, nearly all utilities utilizing climate projections looked at two or three future time periods, often defined by relevance to their planning processes. Typically, projections were made for approximately 30 years for operations or strategic planning and approximately 50 years for infrastructure and capital improvement plans. For example, the SPU study used three time periods (2025, 2050, and 2075); Portland used two time periods (2025 and 2045); and LCRA used two time periods (2050 and 2080). Each time period generally represented an average of 10 of more years of climate data to smooth out year-to-year variation in model output.

4.4.2 Global climate models

After selecting appropriate scenarios, the water utilities generally identified a subset of GCMs to use in their study. GCMs are generally selected from the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP3).[16] CMIP3 contains data contributed by 23 of the world's leading climate models (see Table 1).

Table 1. GCMs in the World Climate Research Programme's CMIP Phase Three

Model IPCC designation	First published	Sponsor	Country
BCC-CM1	2005	Beijing Climate Center	China
BCCR-BCM2.0	2005	Bjerknes Centre for Climate Research	Norway
CCSM3	2005	National Center for Atmospheric Research (NCAR)	USA
CGCM3.1(T47)	2005	Canadian Centre for Climate Modeling and Analysis	Canada
CGCM2.1(T63)	2005	Canadian Centre for Climate Modeling and Analysis	Canada
CNRM-CM3	2004	Meteo-France/Centre National de Recherches Météorologiques (CNRM)	France
CSIRO-MK3.0	2001	Commonwealth Scientific and Industrial Research Organisation (CSIRO) Atmospheric Research	Australia
ECHAM5/MPI-OM	2005	Max Plank Institute for Meteorology	Germany
ECHO-G	1999	Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korea Meteorological Administration (KMA), and Model and Data Group	Germany/ Korea
FGOALS-g1.0	2004	National Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG)/Institute of Atmospheric Physics	China
GFDL-CM2.0	2005	U.S. Department of Commerce/NOAA Geophysical Fluid Dynamics Laboratory (GFDL)	USA
GFDL-CM2.1	2005	NOAA GFDL	USA
GISS-AOM	2004	National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS)	USA

16. Note that CMIP is in the process of updating model outputs in anticipation of the Fifth Assessment Report of the IPCC. The next iteration of CMIP will be called CMIP5 – skipping "CMIP4" – in order to align the numbering with the IPCC reports.

Table 1. GCMs in the World Climate Research Programme's CMIP Phase Three (cont.)

Model IPCC designation	First published	Sponsor	Country
GISS-EH	2004	NASA/GISS	USA
GISS-ER	2004	NASA/GISS	USA
INM-CM3.0	2004	Institute for Numerical Mathematics	Russia
IPSL-CM4	2005	Institut Pierre Simon Laplace	France
MIROC3.2 (high resolution)	2004	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan
MIROC3.2 (medium resolution)	2004	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan
MRI-CGCM2.3.2	2003	Meteorological Research Institute	Japan
PCM	1998	NCAR	USA
UKMO-HadCM3	1997	Hadley Centre for Climate Prediction and Research/Met Office	UK
UKMO-HadGEM1	2004	Hadley Centre for Climate Prediction and Research/Met Office	UK

This climate model output, however, can vary dramatically by region. Consequently, for this and other practical considerations, most water utilities select a subset of climate models to use in their study. Three common methods for selecting models are described below.

One method for selecting climate models is hindcasting, which refers to using climate models to project climate over years for which instrumental data are available. The ability of various models to replicate observed climate is often used as a means of selecting a subset of climate models for use in the study under the justification that those models more accurately model the climate of that watershed or region. For example, in the first phase of its work, the NYCDEP Climate Change Task Force selected three GCMs namely the National Center for Atmospheric Research (NCAR), Goddard Institute of Space Studies (GISS) and European Center Hamburg Model (ECHAM) (NYCDEP, 2008). In the second phase of work, NYCDEP evaluated the ~20 GCMs for various combinations of five meteorological variables (precipitation, average, maximum and minimum temperatures and wind speed), over four seasons using probability based skill scores. Since no single model performs best for all variables and seasons they arrived at the most objective way to choose a subset of models to identify the models with the highest mean skill scores (averaged across all variables).

A second method for selecting climate models is to purposefully select models that project a range of climate conditions. This was the strategy employed in the SPU study (Polebitski et al., 2007a). The three GCM-scenario combinations selected by the UW-CIG were the GISS Model ER/B1 combination, the MPI ECHAM5/A2 combination, and the Institut Pierre Simon Laplace (IPSL) CM4/A2 combination. These models have performed well in other studies when replicating the temperature and precipitation trends of the Pacific Northwest during the 20th century (Mote et al., 2005). The MPI ECHAM5/A2 model represents a middle-of-the-road scenario with moderate warming and precipitation increase. The IPSL-CM4/A2 model scenario is significantly wetter and warmer, and the GISS-ER/B1 scenario is slightly drier and warmer.

The LCRA study (CH2M Hill, 2008) used a third method for selecting climate models that is effectively a hybrid of the two methods described above. Initially, six models were selected for further assessment based on expert judgment of the leading models for California selected by researchers at the Scripps Institute of Oceanography: NCAR CCSM3.0, NCAR PCM1, GFDL CM2.1, CNRM CM3, CCSR MICRO3.2 (medres), and MPI ECHAM5.[17] Projected changes in temperature and precipitation from all six models under two emissions scenarios (A2 and B1) and two time periods (2050 – averaged 2036–2065; and 2080 – averaged 2066–2099) were plotted onto a grid representing the 10th and 90th percentile of all 112 downscaled model simulations from the U.S. Bureau of Reclamation. Scenarios that plotted consistently outside of this range were discarded, resulting in the selection of two climate models for the LCRA study that were considered to provide a reasonable range of potential climate change effects in the Colorado River Basin.

4.4.3 Downscaling

Finally, all climate projections must be downscaled to the spatial and temporal resolution to be useful inputs into water system models. This is generally done using one of three downscaling methodologies: simple, statistical, or dynamic downscaling (see Box 2).

For example, the PWB study used simple downscaling. It started with relatively coarse spatial resolution model results – on the order of three degrees or approximately 300-km grids (Palmer and Hahn, 2002). UW downscaled the data to one-degree or approximately 100-km grids using the Symap algorithm. However, even at one degree, the model results were still coarse. Consequently, the climate change signal for each model and time period was calculated as the difference between average monthly temperature and precipitation from a control run simulating current climate and future climate model predictions. This yielded delta values by month for 2025 and 2045 that indicated the modeled change in temperature and precipitation. These deltas were then applied to an observed climate dataset used by UW as input into its Distributed Hydrology, Soil-Vegetation Model (DHSVM) to characterize the hydrology of PWB’s Bull Run watershed. This represents a form of simple downscaling because it used coarse GCM data and related them to the observed record to define a dataset at the spatial and temporal scale of the utility’s models.

17. NCAR CCSM3.0 and GFDL CM2.1 were ultimately chosen for use in the LCRA study.

Box 2. Downscaling methodologies

Simple downscaling involves adding projected changes in temperature and precipitation from GCMs to weather observations for a historical control period. This preserves observed spatial differences and locally observed seasonality of weather, and allows for the selection of different historic control periods for different purposes (e.g., a drought year or a year of heavy flooding). However, this method does not account for differences in climate change within a grid box.

Statistical downscaling is a method by which climate change can be projected for a particular location or small geographic area. Variables found in GCMs such as pressure are correlated with observations such as observed temperature or precipitation. The correlation uses GCMs' simulation of current climate. This correlation is used to project changes in the predicted variable(s) based on the estimated changes in GCMs. Statistical downscaling is computationally easier than dynamic downscaling, but does not allow for changes in the relationship between the predictor and predicted variables.

Dynamic downscaling uses RCMs to give higher resolution projections than GCMs. These models are like GCMs, but simulate only a portion of the globe and can therefore have much smaller grid boxes than GCMs and can incorporate sub-GCM-grid scale variables (e.g., mountain ranges, lakes). RCMs are "nested" within GCMs using "boundary conditions" from GCMs to drive them. RCMs typically have resolutions of 50 km or less. RCMs have the advantage of simulating dynamic relationships between climate variables, but require extensive computing power.

A key limitation of all three downscaling methods is that they depend on GCMs. Errors in GCMs are typically not corrected by downscaling techniques, although each technique will supply sub-GCM-grid scale variations in climate.

NYCDEP used a similar change factor approach, using the difference in daily GCM control and future scenarios to calculate change factors that were subsequently applied to local meteorological records used to drive watershed and reservoir models. In the first phase of NYCDEP climate change work, monthly change factors (additive or multiplicative) were calculated from pooled daily data associated with each month in each scenario. In the second phase of the work the change factor methodology was evaluated, and an improved method was developed that calculated 25 additive change factors for 25 equally spaced bins of the frequency distribution associated with each month's pooled data. City of Boulder Utilities Division also used simple downscaling, but combined GCM output with paleoclimate reconstructions.

The LCRA study used a different technique for downscaling. The selection of GCMs for the LCRA study ultimately led to eight datasets – two models (NCAR CCSM3.0 and GFDL CM2.1), two scenarios (A2 and B1), and two time periods (2050 – averaged 2036–2065; and 2080 – averaged 2066–2099). These eight datasets were statistically downscaled from the model grid scale to regional or watershed scales by retrieving the appropriate temporal-spatial data in the archived U.S. Bureau of Reclamation downscaled dataset (1/8 degree; 12-km grids).[18] A suite

18. The Bureau of Reclamation developed an archive of statistically downscaled and bias-corrected climate projections for the contiguous 48 states at 1/8 degree resolution, which is what was used in the LCRA study (see http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html). It should be noted that it is possible to statistically downscale GCM projections using a variety of techniques independent of the U.S. Bureau of Reclamation dataset. The SPU study provides an example of a different technique.

of data processing tools and geographic information systems were applied to these data to delineate the datasets for the State of Texas and the Colorado River Basin. Simulated future climate was analyzed by comparing the 2050 and 2080 periods with a reference period of 1970–1999 (CH2M Hill, 2008). This use of sophisticated statistical techniques to downscale GCM output to local watersheds is known as statistical downscaling.

The SPU study conducted its own method of statistical downscaling (Polebitski et al., 2007b). First, the SPU study did a bias correction of GCM simulation of hindcast climate using historic data. Those bias corrections were then applied to coarse (GCM grid scales) future climate data. The bias-corrected coarse grid was then related to a regional grid (1/8 degree) using scaling factors (additive factors for temperature and multiplicative factors for precipitation). The regional, bias-corrected future climate data are then related to specific weather station locations and again bias-corrected to yield a monthly time-series at the station level. These station level changes can be combined with historic data to yield scenarios of daily data that preserve historic climate variability.

For its statistical downscaling, the MWRA used a non-parametric method for generating the requisite daily weather sequences, specifically the K-nearest neighbor (K-NN) bootstrapping technique (Yates et al., 2003). This method samples the historical record in order to generate a large set of individual weather sequences that replicates the statistical characteristics of local weather but are consistent with the range of GCM-derived temperature and precipitation trends. Using probability density functions derived from 21 GCMs following the procedure outlined in Tebaldi et al. (2005), the K-NN algorithm was used to develop individual sequences of weather variables for the key weather station locations that are used by the system simulation model (WEAP) of MWRA's supply system.

The final downscaling methodology is dynamic downscaling. Dynamic downscaling uses RCMs to translate GCM output into higher-resolution regional climate data. Dynamic downscaling captures the effects of mesoscale features such as narrow mountain ranges, complex land/waterbody interactions, or variations in land use and land cover in a way that GCM currently cannot. Until recently, the computing power necessary for dynamic downscaling to provide useful data was prohibitive and the results were not high-resolution enough to improve upon statistical downscaling approaches. Current research into RCMs and dynamic downscaling shows promise. For example, UW-CIG is engaged in research to develop a fully functional RCM for the Pacific Northwest. NYCDEP also worked with Columbia University's Center for Climate Systems Research (CCSR) and the City University of New York to establish a dynamic downscaling strategy for future assessments.

4.4.4 Combining methods: Climate projections with paleoclimate data

The study conducted for the City of Boulder combined climate model output with paleoclimate data (Smith et al., 2009). To our knowledge, this is the first study to do so in the United States. The study matched paleoclimate reconstructions of streamflow in Boulder Creek with years during the observed climate record that had similar streamflow. The climate in the similar years was used as a proxy for the climate of the paleorecord. In other words, the reconstruction of streamflow in a paleo year (e.g., 1635) was then matched to a year in the observed record with a similar annual streamflow. A best match between reconstructed streamflow and years in the observed record did not always exist. Therefore, the technique used a random process to select years from the observed record with similar characteristics. The model was run many times to yield different combinations of the observed record and mimic the reconstruction. This introduces many combinations of reconstructions, which allows for more variability in results.

The Boulder study used a simple downscaling of GCM data. The changes in temperature and precipitation were added to or multiplied by temperature and precipitation, respectively, in the proxy record. This yielded a set of climate change scenarios that mimicked the year-to-year variability of the paleorecord, but with long-term average changes in climate from the GCMs imposed on the set.

The reconstruction of streamflow for Boulder Creek utilized a 437-year record from 1566 to 2002 (Woodhouse and Lukas, 2006b). The reconstruction technique estimates 65% (i.e., has an R^2 of 0.65) of the observed streamflow variance.

The study used output from three GCMs under three emissions scenarios for the decades of the 2030s and 2070s. The selected emissions scenarios (A2, A1B, and B1) represented a wide range of future conditions. As with SPU, the GCMs were selected to capture a wide range of potential changes in regional climate. While all climate models project that the central Rocky Mountains and adjacent plains will become warmer, the models disagree as to whether precipitation will increase or decrease. To overcome this, the study used a relatively wet model (the Canadian Climate Model), a relatively dry model (GFDL Version 0), and a model roughly in the middle of the range of model output (GFDL Version 1).

5. Modeling Changes in Water Resources

Water utilities use a variety of models and analytical techniques for various purposes. As a general organizational distinction, it simplifies things to examine how a utility approaches water quantity and water demand separately.[19]

5.1 Water Quantity

Water utilities may use one or more water management model(s) for day-to-day operations and long-term water planning. Many, but not all, also use a hydrologic model to translate temperature and precipitation data into streamflow, reservoir storage, evaporative loss, and other variables input directly into water system management models. The specific constellation of models used by a utility often determines what climate information it needs to carry out a climate change vulnerability assessment.

PWB, for example, input temperature and precipitation data into the DHSVM to generate averaged annual hydrographs. DHSVM is a physically based hydrology model that characterized the entire Bull Run watershed into 150-m grid cells with grid-specific data on soil and vegetation type, soil depth, vegetation height, and surface elevation and slope. DHSVM represents the more detailed end of utility hydrology models that have been empirically characterized for a number of parameters in addition to temperature and precipitation.

PWB applied the UW-CIG developed climate altered streamflows through DHSVM and then input the data into PWB's Supply and Transmission Model (STM), an operational model of PWB's terminal water storage and groundwater resources. STM operates at a daily timestep and simulates the flow of water throughout the water transmission system using seasonally varying rule curves for the reservoirs, as well as modeling water releases for hydropower production and instream flows. Groundwater operations are coordinated with reservoir operations to enable the investigation of a variety of operating alternatives using variables such as length of drawdown period, amount of groundwater pumped during drawdown, minimum storage during drawdown, and water used during drawdown. As a part of a Water Research Foundation project, the PWB used the STM data sets to look at how the WEAP platform worked in comparison with the outputs of the STM, however, the WEAP model was not used for the initial climate change study done by UW-CIG. For purposes of this analysis it is important to note the use of multiple operational models for different purposes by a single utility.

19. Some utilities in this study, such as NYCDEP, were also concerned about climate change effects on water quality. However, generally speaking, water quality involves a greater variety of models (e.g., reservoir specific eutrophication models) and/or micro-climate processes that often occur at a higher resolution than can be captured by current GCMs or RCMs (e.g., intense precipitation events). The scope of this report did not allow us to fully explore water quality modeling.

In order to use SPU's systems model, climate change parameters needed to be converted to inflow. UW-CIG used the DHSVM hydrology model to produce climate-altered hydrologic datasets based on climate model output for use in the Conjunctive Use Evaluation (CUE). SPU then used the results from DHSVM in its CUE systems model – a weekly timestep simulation model of the Cedar and Tolt River systems – for water supply planning. CUE is used for calculating and evaluating the firm yield[20] and reliability of Seattle's water supply system and potential future water supply projects. CUE results indicated that yield decreased under all climate change scenarios for all time periods. SPU also ran several planning scenarios through CUE to determine whether available supply could be increased to compensate for anticipated shortfalls.

The use of river gauge data as input into CUE was a policy decision for SPU, because it also has the capability to use the Seattle Forecast Model (SEAFM), a proprietary hydrology model calibrated to the SPU watersheds and used in operational forecasting and operations planning. UW-CIG chose to use DHSVM instead of SEAFM (or its successor models) for its climate change vulnerability analysis because UW-CIG developed DHSVM and it was available to all watersheds in the broader UW-CIG led regional study in which SPU participated.

NYCDEP has a very complex modeling environment. It currently does analysis using the Variable Source Loading Function (VSLF) or the SWAT watershed models. These can in turn provide inputs to one of two reservoir models: a one-dimensional reservoir eutrophication model; or a two-dimensional reservoir turbidity transport model (CEQual W2). The OASIS reservoir system operation model requires measured or simulated water inputs to the reservoirs and simulates the storage and transfer of water between the 19 reservoirs comprising the NYC water supply system. The watershed models, take daily temperature and precipitation data to generate streamflow and evapotranspiration, as well as a number of water quality parameters. Outputs of the watershed models can be used to drive both the OASIS system model and reservoir water quality models. A knowledge of reservoir operations is an important determinate of reservoir water quality, and a needed input to the reservoir models. For future climate simulations, where historical operations are not known, OASIS simulation are needed to specify reservoir operation scenarios associated with a given climate scenario. All of the above models were in use at NYCDEP to evaluate the impacts of changes in watershed management, land-use, and reservoir operation policies. This integrated modeling system was easily adapted for evaluation of the effects of climate change, once credible future scenarios of the meteorological variables needed to drive the models were available.

5.2 Water Demand

Changes in climate can also have an important effect on water demand. Demand means different things to different utilities depending upon their customer base and the timeframe of their assessment. Several utilities evaluated in this report provided interesting examples of different

20. Firm yield is based on the 98% reliability standard.

approaches or concerns to project changing water demand. EBMUD was focused primarily on exterior water use by urban and suburban water customers, while SPU and PWB were focused on the balance between population growth and climate altered demand over time.

According to EBMUD, customer demands are projected to vary predominantly based on temperature change. While indoor water use is not expected to change significantly with global warming, outdoor water use could change dramatically. To account for this, 2040 customer demands were re-normalized using a projected temperature increase of 2.15ºC (3.87ºF) between 2005 and 2040 with no change in precipitation. EBMUD's analysis indicated that a 20% reduction in precipitation had little influence on overall customer demands compared to the projected temperature change. The demand model suggested a 3.6% increase in customer demands by the year 2040 (EBMUD, 2009).

The SPU study examined the effect of climate change on water demand using a dual approach of regression analysis and forecast modeling. First, SPU performed a regression analysis of peak season consumption for 1982–2007 using monthly consumption data, maximum temperature, and rainfall at SeaTac Airport for May through September. This relationship was assumed to hold in the future. SPU had already developed a demand forecasting model for its *2007 Water System Plan*, which forecasted non-climate altered demand change over time. Under this model, demand was forecasted to decrease below historic levels through 2050, but increase above historic levels by 2075. Applying the results of the regression analysis to these forecasts adjusts demand slightly upward due to climate change in 2025 and 2050. But in 2075, the climate-induced increase becomes more significant on top of the additional forecasted upswing from the non-climate altered demand model.

In 2002, PWB examined the effects of climate-altered streamflow on system operations from a demand perspective using their STM. The evaluation investigated the climate and population growth impact on demand and supply separately and then jointly to discern the discrete effects of climate change. The process for calculating the climate impact on demand was derived from the Joint Institute on the Study of Atmosphere and Oceans (JISAO) report, *Impacts of Climate Variability and Change in the Pacific Northwest* (JISAO-CIG, 1999). This study used seven featured years and the ECHAM4 climate scenario for detailed analysis. Growth in demand not considering changes in climate decreased the average minimum storage dramatically. This was exacerbated (approximately doubled) by the impacts of climate on hydrology and demand.

PWB also utilized their water demand econometric model to estimate near- and long-term water demand that established a relationship between total water demand and selected economic, demographic, seasonal, and day-to-day weather variables. This econometric model is used as a forecasting tool by projecting changes in the economic and demographic variables. In order to gauge the effects of climate change on demand, past weather years with patterns that approximate climate projections are selected to forecast future demands. For example, in projecting demands in 2050, PWB uses 1948 as the wettest, or best-case scenario (corresponding to a 3.67ºF/2.04ºC increase in average peak season temperature), 1980 as a middle-of-the-road scenario (corresponding to a 4.83ºF/2.68ºC increase in average peak season temperature), and

1991 as the driest, or worst-case scenario (corresponding to a 6.72ºF/3.73ºC increase in average peak season temperature).

6. Summary

We investigated assessments of climate change vulnerability conducted by eight utilities to determine the emergent characteristics of water utility climate change vulnerability assessments (see Table 2). We found that two standard approaches were used for the risk assessments: the top-down modeling assessment and the bottom-up threshold analysis. While both methods produce important risk information, the selection of an assessment model is often determined by available fiscal and technical resources as well as the policy environment faced by the utility. These two approaches are not mutually exclusive, and are often run in series or in parallel to provide a robust vulnerability assessment. Notably, top-down assessments come in a variety of types, including scenario analyses, sensitivity analyses, and paleoclimate or historic analyses.

Sources of climate data used by the utilities included the instrumental record, paleoclimate data, literature reviews, and climate projections from GCMs. While information from each of these sources played an important role in one or more utility vulnerability assessments, climate projections offered the most computationally demanding approach. Climate projections required the selection of GHG emissions scenarios and defined time periods, the selection of a subset of GCMs (typically by hindcasting, selecting a broad range of outputs, or eliminating outliers), and downscaling the GCM data to the spatial and temporal scale necessary for input into utility hydrology, management, or operations models through simple, statistical, or dynamical downscaling techniques.

Finally, the climate information was run through utility-specific models to determine the effects of projected climate conditions on water supply and demand. We found that on the supply side, the models typically used included both hydrology and operational or management models. Demand modeling by utilities ranged from service-area-specific correlations between customer demand and temperature/precipitation to utility-specific demand models developed for long-range planning.

Table 2. Aspects of utility vulnerability assessment efforts

	Assessment approach	Climate model selection	GHG emissions scenarios	Downscaling	Time periods	System models	Runoff models
Boulder	Top-down (paleo)	Purposeful selection for range	A2, A1B, B1	Simple	2030, 2070	Boulder Creek Model	CLIRUN
Denver Water	Top-down (sensitivity, scenario in process)	Current study: Purposeful selection for range	Current study: A2, A1B, B1	Current study: statistical	In process study: 2040 and 2070	PACSM, ESP	Sacramento Soil Moisture coupled with Anderson Snow-17, WEAP
MWRA	Top-down	All models (Yates/NCAR project)	A1B	Statistical	Weekly projections through 2060	WEAP	abcd watershed model
NYCDEP	Top-down (scenario)	Probability based skill score approach	A2, A1B, B1	Delta change factor methodology by month and frequency distribution, statistical	2046-2065 and 2081-2100	OASIS, CEQual W2, 1-D Eutrophication	VSLF, SWAT
PWB	Top-down (sensitivity)	Purposeful selection for range	1% annual increase in CO_2[a]	Statistical	2025, 2045	STM, WEAP	DHSVM
SPU	Top-down (scenario)	Purposeful selection for range	2007 study: A2, B1, 2002 study: A2	Statistical	2007 study: 2000, 2025, 2050, 2075 2002 study: 2000, 2020, 2040	Conjunctive Use Evaluation (CUE)	DHSVM
LCRA	Bottom-up (scenario)	Hindcast and purposeful selection for range	A2, B1	Statistical (Bureau of Reclamation dataset)	2050, 2080	WAMWRAP,	Variable Infiltration Capacity
EBMUD	Bottom-up (sensitivity)[b]	Conducted sensitivity analysis	N/A	N/A	N/A	EBMUDSim, WEAP	N/A

a. The 1% annual increase in CO2 scenario was often used prior to development of the SRES scenarios.

b. Because EBMUD chose to use a sensitivity analysis, the climate modeling aspects of this table are not applicable.

7. Recommendations for Further Study

This report describes a range of practices used by eight water utilities to evaluate the effects of climate change on water quantity and water demand using hydrological, management and operational models. Climate change is a complex issue and will require ongoing work to establish reliable practices for incorporating climate change into water utility decisions and planning. Additional questions to develop this line of inquiry further include:

- How are decision makers and rate payers responding to these types of analyses?
- Would the results vary if different methods were used by the same utility?
- How do the different methods compare in effectiveness, over time?
- What other decisions, utility models, etc. need climate vulnerability assessments?
- How are vulnerability assessments being conducted for understanding climate impacts on managing:
  - Water quality?
  - Intense precipitation and storms (stormwater, floods, wind)?
  - Sea level rise?

As other water resource managers gain more experience with climate vulnerability assessments, it would benefit the water resource management field to continue to document lessons learned in an effort to create, over time, a solid foundation of acceptable industry practices.

8. References

Barsugli, J., C. Anderson, J.B. Smith, and J.M. Vogel. 2009. *Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change. Final Report.* Prepared for Water Utility Climate Alliance. December.

CH2M Hill. 2008. *Climate Change Study: Report on Evaluation Methods and Climate Scenarios. Final Report*. Lower Colorado River Authority and San Antonio Water System. November.

Dettinger, M.D. 2005. From climate-change spaghetti to climate-change distributions for 21st Century California. *San Francisco Estuary and Watershed Science* 3(1). Available: http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4.

EBMUD. 2009. *WSMP 2040: Water Supply Management Program 2040 Plan*. East Bay Municipal Utility District. October.

Freas, K., B. Bailey, A. Munevar, and S. Butler. 2008. Incorporating climate change in water planning. *Journal of the American Water Works Association* 100:6. June.

Garrick, D. and K. Jacobs. 2005. Tree-ring records inform water management decisions: Workshop strives for better integration of past with present. *Southwest Climate Outlook*. May.

Hydrosphere. 2003. *Simulation of Hypothetical Climate Change Scenarios Using the Boulder Creek Watershed Model*. Hydrosphere Resource Consultants (now AMEC), Boulder, CO.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, UK and New York.

JISAO-CIG. 1999. *Impacts of Climate Variability and Change: Pacific Northwest*. A Report of the Pacific Northwest Regional Assessment Group for the US Global Change Research Program. Joint Institute for the Study of Atmosphere and Oceans – Climate Impacts Group. Office of Global Programs at the National Oceanographic and Atmospheric Administration. Seattle, WA. November.

Karl, T.R., J.M. Melillo, and T.C. Peterson. 2009. *Global Climate Change Impacts in the United States*. Cambridge University Press, New York.

Major, D.C., R. Horton, and C. Rosenzweig. 2007. *Integrated Modeling Project for Water Quantity and Quality: Guidelines for Project Final Report*. Climate Impact Assessment of Environmental Infrastructure Systems. New York City Department of Environmental Protection. June 29.

Maurer, E.P., L. Brekke, T. Pruitt, and P.B. Duffy. 2007. Fine-resolution climate projections enhance regional climate change impact studies. *Eos Trans. AGU 88*(47):504.

Means III, E.G., M.C. Laugier, and J.A. Daw. 2010. *Evaluating Decision Support Planning Methods for Incorporating Climate Change Uncertainties into Water Planning. Final Report.* Prepared for Water Utility Climate Alliance. January.

Meko, D.M. and C.A. Woodhouse. 2005. Tree-ring footprint of joint hydrologic drought in Sacramento and Upper Colorado River basins, western USA. *Journal of Hydrology* 308:196-213.

Miller, K. and D. Yates. 2006. *Climate Change and Water Resources: A Primer for Municipal Water Providers*. Jointly sponsored by Awwa Research Foundation, Denver, CO and University Corporation for Atmospheric Research, Boulder, CO. Awwa Research Foundation, American Water Works Association, and IWA Publishing.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: Whither water management? *Science* 319:573-574.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks. 2010. The next generation of scenarios for climate change research and assessment. *Nature* 463:747-756.

Mote, P.W., E. Salathe, and C. Peacock. 2005. *Scenarios of Future Climate for the Pacific Northwest*. University of Washington: Climate Impacts Group.

Nakićenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Raihi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi. 2000. *Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, New York.

UCAR. 2007. North American Regional Climate Change Assessment Program. Available: http://www.narccap.ucar.edu/. Accessed May 28, 2010.

NRC. 2002. *Abrupt Climate Change: Inevitable Surprises*. National Academies Press: Washington, D.C. Available: http://www.nap.edu/openbook.php?isbn = 0309074347.

NYCDEP. 2008. *The New York City Department of Environmental Protection Climate Change Program Assessment and Action Plan: Report 1*. May.

Palmer, R.N. 2007. *Final Report of the Climate Change Technical Committee*. A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA.

Palmer, R.N. and M. Hahn. 2002. *The Impacts of Climate Change on Portland's Water Supply: An Investigation of Potential Hydrologic and Management Impacts on the Bull Run System*. Portland Water Bureau. January.

Polebitski, A., L. Traynham, and R.N. Palmer. 2007a. *Technical Memorandum #4: Approach for Developing Climate Impacted Meteorological Data and its Quality Assurance/Quality Control*. A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA.

Polebitski, A., M.W. Wiley, and R.N. Palmer. 2007b. *Technical Memorandum #2: Methodology for Downscaling Meteorological Data for Evaluating Climate Change*. A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process, Seattle, WA.

Smith, J.B., K. Strzepek, L. Rozaklis, C. Ellinghouse, and K.C. Hallett. 2009. *The Potential Consequences of Climate Change for Boulder Colorado's Water Supplies*. Prepared for NOAA's Climate Program Office. February.

Strange, E.M., D.R. Lane, and C.N. Herrick. 2009. Utility Guidance for Mitigating Catastrophic Vegetation Change in Watersheds. Project #4009. Water Research Foundation, Denver, CO.

Stratus Consulting and MWH Global. 2009. *Implications of Climate Change for Adaptation by Wastewater and Stormwater Agencies*. Water Environment Research Foundation Report No. CC2R08.

Tebaldi, C., J.M. Arblaster, K. Hayhoe, and G.M. Meehl. 2006. Going to extremes: An intercomparison of model-simulated historical and future change extremes. *Climatic Change* 79:185-211.

Tebaldi, C., R.L. Smith, D. Nychka, and L.O. Mearns. 2005. Quantifying uncertainty in projection of regional climate change: A Bayesian approach to analysis of multi-model ensembles. *Journal of Climate* 18:1524-1540.

TreeFlow. 2010. Streamflow reconstructions from treerings website. Available: http://treeflow.info/. Accessed March 30, 2010.

U.S. EPA. 2009. *Proceedings of the First National Expert and Stakeholder Workshop on Water Infrastructure Sustainability and Adaptation to Climate Change*. Publication No. EPA 600/R-09/010. Available: http://www.epa.gov/nrmrl/wswrd/wqm/wrap/workshop.html.

Woodhouse, C.A. and J.J. Lukas. 2006a. Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning. *Climatic Change.* DOI: 10.1007/s10584-006-9055-0.

Woodhouse, C. and J. Lukas. 2006b. Streamflow Reconstructions for Boulder Creek, South Boulder Creek, and the Colorado River. Report to City of Boulder and Hydrosphere Resource Consultants. AMEC Consulting, Boulder, CO.

WRF. 2010a. Analysis of Changes in Water Use Under Regional Climate Change Scenarios. Project #4263. Project in progress; completion year 2013. Water Research Foundation, Denver, CO.

WRF. 2010b. Estimating Salinity Effects Due to Climate Change on the Georgia and South Carolina Coasts. Project #4285. Project Description; completion year 2012. Water Research Foundation, Denver, CO.

WRF. 2010c. Evaluating Effects of Climate Change on Water Utility Planning Criteria and Design Standards. Project #4154. Project Description and Abstract; completion year 2010. Water Research Foundation, Denver, CO.

WRF. 2010d. Incorporating Climate Change Information in Water Utility Planning: A Collaborative, Decision Analytic Approach. Project #3132. Project Description and Abstract; completion year 2010. Water Research Foundation, Denver, CO.

WRF. 2010e. Project Snapshot: Joint Front Range Climate Change Vulnerability Study #4205. Available: http://www.waterresearchfoundation.org/research/TopicsAndProjects/projectSnapshot.aspx?pn = 4205. Accessed March 30, 2010.

WRF. 2010f. Water Utilities and Climate Change: A Research Workshop on Effective System Adaptation. Project #4228. Project Description; completion year 2010. Water Research Foundation, Denver, CO.

Yates, D., S. Gangopadhyay, B. Rajagopalan, and K. Strzepek (2003). *A technique for generating regional climate scenarios using a nearest neighbor algorithm,* Water Resources Research, 39(7), 1199.